Simulations of NDCX-II Targets for Warm Dense Matter and Heavy Ion Fusion Physics*

J. J. Barnard, A. Friedman, L. J. Perkins (LLNL), F. M. Bieniosek, M. J. Hay, E. Henestroza, B. G. Logan, R. M. More, P. A. Ni, S. F. Ng, S. S. Yu (LBNL) S. A. Veitzer (Tech-X)

18th International Symposium on Heavy Ion Fusion

Darmstadt, Germany

August 30 – September 3, 2010

Fusion Energy Sciences

The Heavy Ion Fusion Science Virtual National Laboratory

BERKELEY LAB

PPPL PRINCETON PLASMA PHYSICS LABORATORY

* This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, by LBNL under Contract DE-AC02-05CH11231, and by PPPL under Contract DE-AC02-76CH03073.

Outline:

1. Planar targets: exploiting volumetric ion beam energy deposition

2. Machine tradeoffs: ion energy, pulse energy, and pulse duration

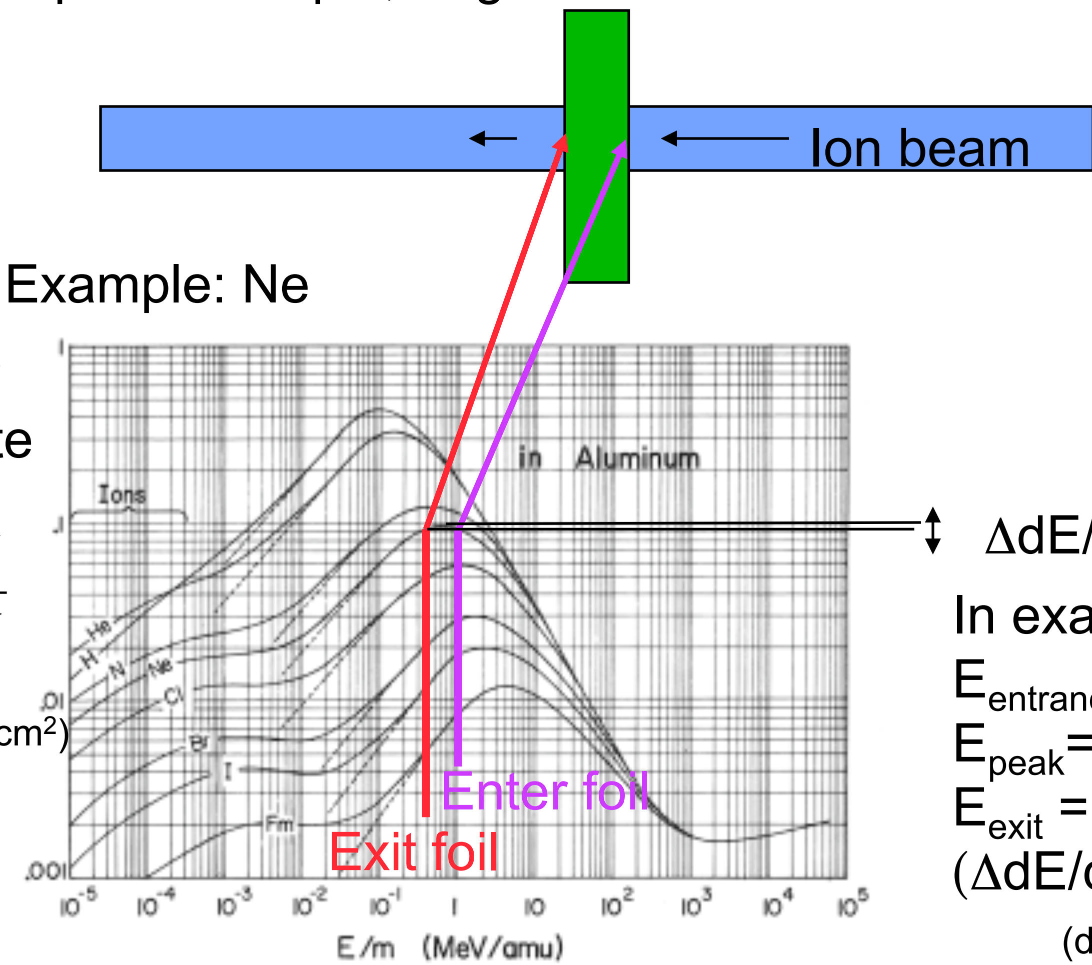
3. WDM experiments:
   - Equation of state

4. IFE relevant experiments:
   - Ion coupling: using ramped ion energy to maximize shock strength
   - Hydrodynamic stability

5. Other target geometries: cylindrical and spherical bubbles, metallic foams

Strategy: maximize uniformity and the efficient use of beam energy by placing center of foil at Bragg peak

In simplest example, target is a foil of solid or “foam” metal



Energy loss rate

$$-\frac{1}{Z^2}\frac{dE}{dX}$$

(MeV/mg cm^2)

Energy/Ion mass (MeV/amu)

fractional energy loss can be high and uniformity also high if operate at Bragg peak (Larry Grisham, PPPL)

$\Delta dE/dX \propto \Delta T$

In example,

$E_{entrance}$=1.0 MeV/amu

E_{peak}= 0.6 MeV/amu

E_{exit} = 0.4 MeV/amu

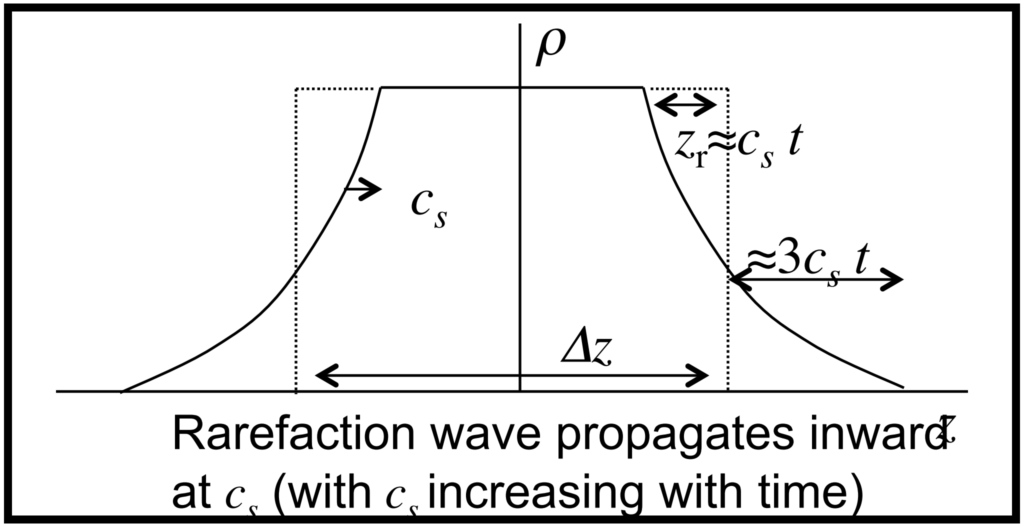
$(\Delta dE/dX)/(dE/dX) \approx 0.05$

(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, A7, 233 (1970))

Pulse duration must be short to avoid hydrodynamic expansion and cooling

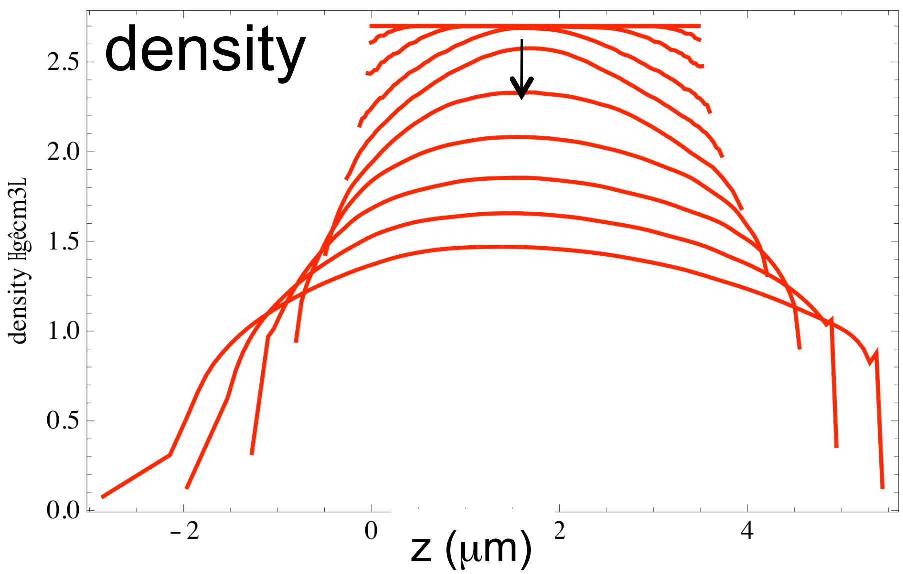
$$\tau_{\text{pulse}} < \Delta z / c_s$$

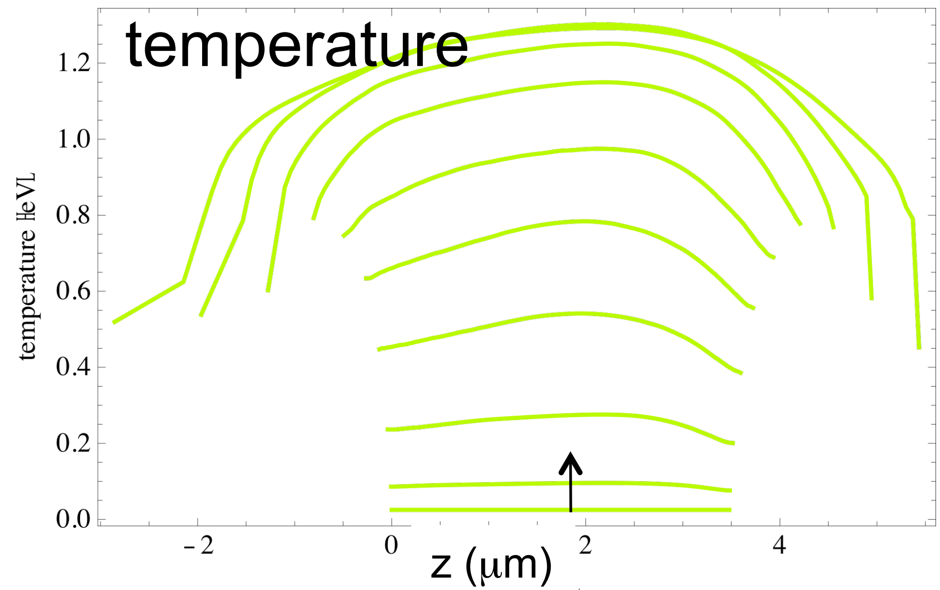
Here: τ_{pulse} = pulse duration
Δz = thickness of target
c_s = sound speed



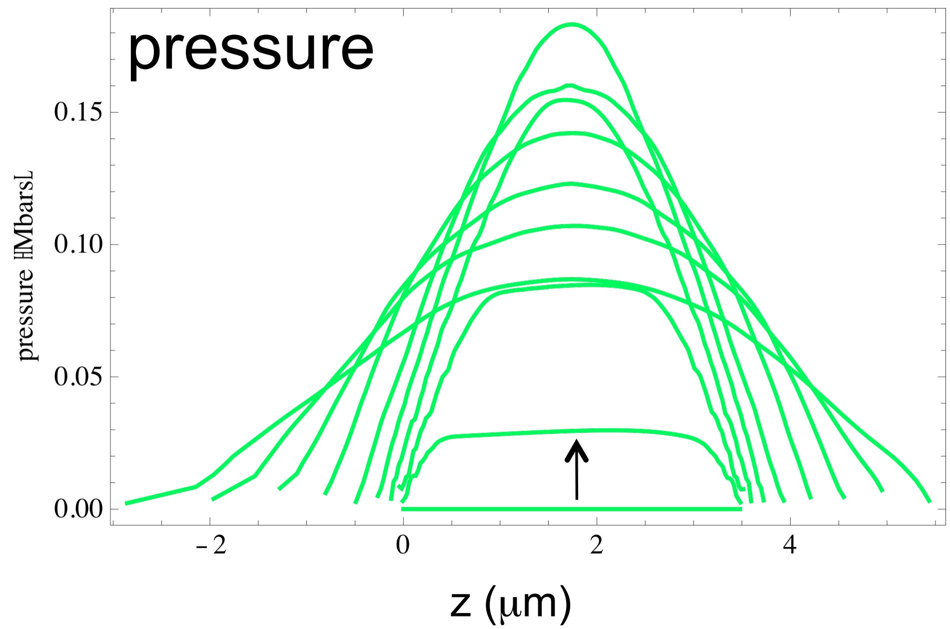
The heating pulse should be delivered in a time comparable to or shorter than the time it takes for a rarefaction wave to reach an interior point.

Evolution of center of 3.5 μ thick Al foil over the heating phase (1 ns) using QEOS (assuming advanced NDCX II)



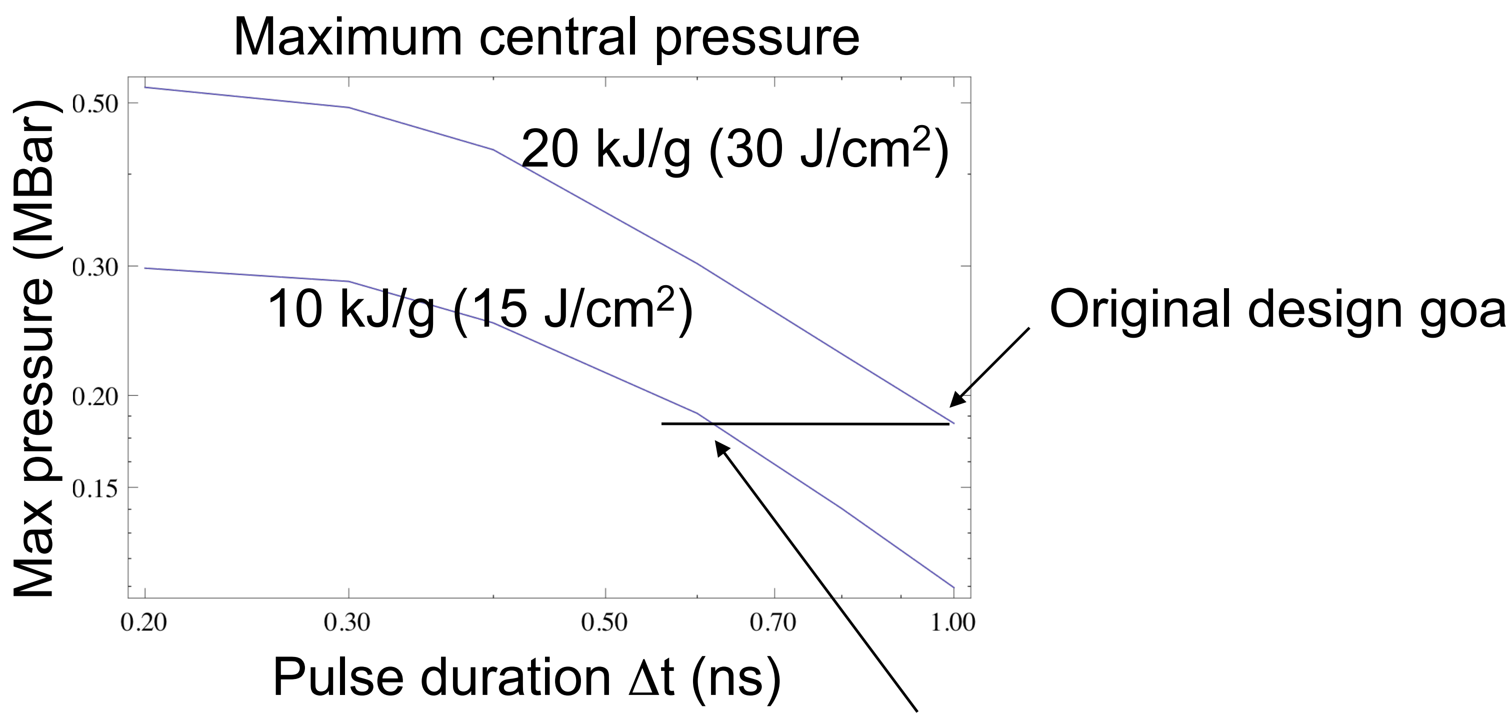


Snapshots separated by 0.1 ns



Recent short pulse configurations of NDCX-II reach high pressures at lower fluence via shorter pulse Δt

One figure of merit is central pressure in the foil, since it reflects both high density and high temperature



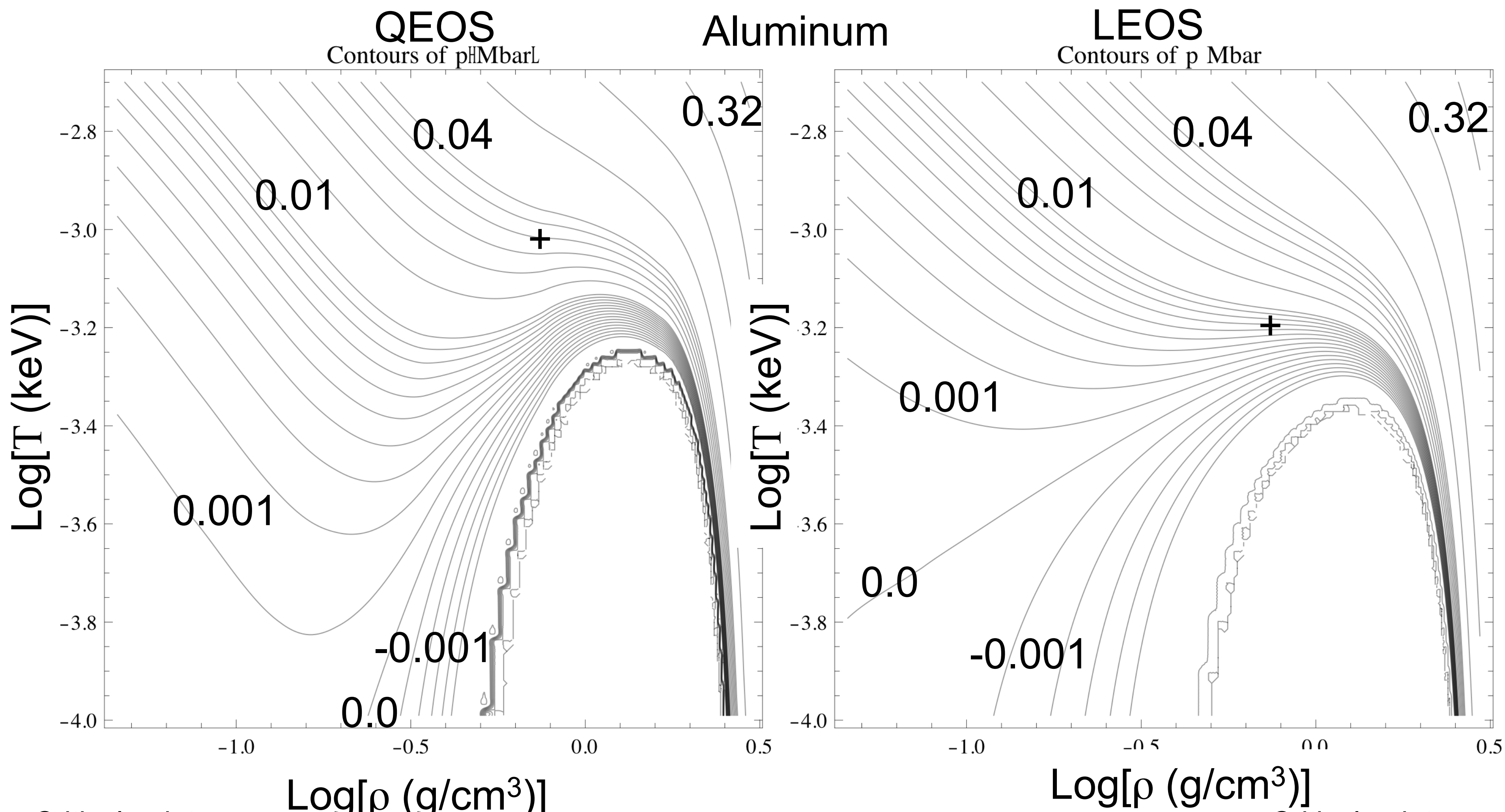
Example: If the pulse duration is reduced to 0.62 ns and the pulse energy reduced to 10 kJ/g, the same central pressure is reached.

NDCX-II potential performance for "well tuned" configurations

	NDCX-I (bunched beam)	NDCX-II construction project			NDCX-II 21-cell (enhanced)
		12-cell (baseline)	15-cell ("probable")	18-cell ("possible")	
Ion species	K^+ (A=39)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)
Total charge	15 nC	50 nC	50 nC	50 nC	50 nC
Ion kinetic energy	0.3 MeV	1.2 MeV	1.7 MeV	2.4 MeV	3.1 MeV
Focal radius (50% of beam)	2 mm	0.6 mm	0.6 mm	0.6 mm	0.7 mm
Duration (bi-parabolic measure = $\sqrt{2}$ FWHM)	2.8 ns	0.9 ns	0.4 ns	0.3 ns	0.4 ns
Peak current	3 A	36 A	73 A	93 A	86 A
Peak fluence (time integrated)	0.03 J/cm^2	13 J/cm^2	19 J/cm^2	14 J/cm^2	22 J/cm^2
Fluence w/in 0.1 mm diameter, w/in duration		8 J/cm^2	11 J/cm^2	10 J/cm^2	17 J/cm^2
Max. central pressure in Al target		0.07 Mbar	0.18 Mbar	0.17 Mbar	0.23 Mbar
Max. central pressure in Au target		0.18 Mbar	0.48 Mbar	0.48 Mbar	0.64 Mbar

NDCX-II WARP simulations by Grote, Sharp, and Friedman

WDM experiments: An example of two significantly different equations of state

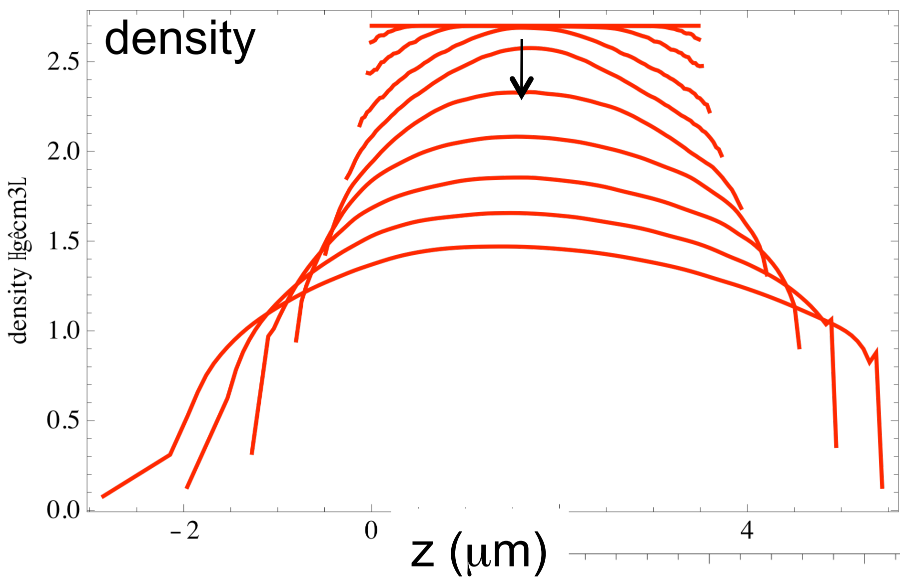


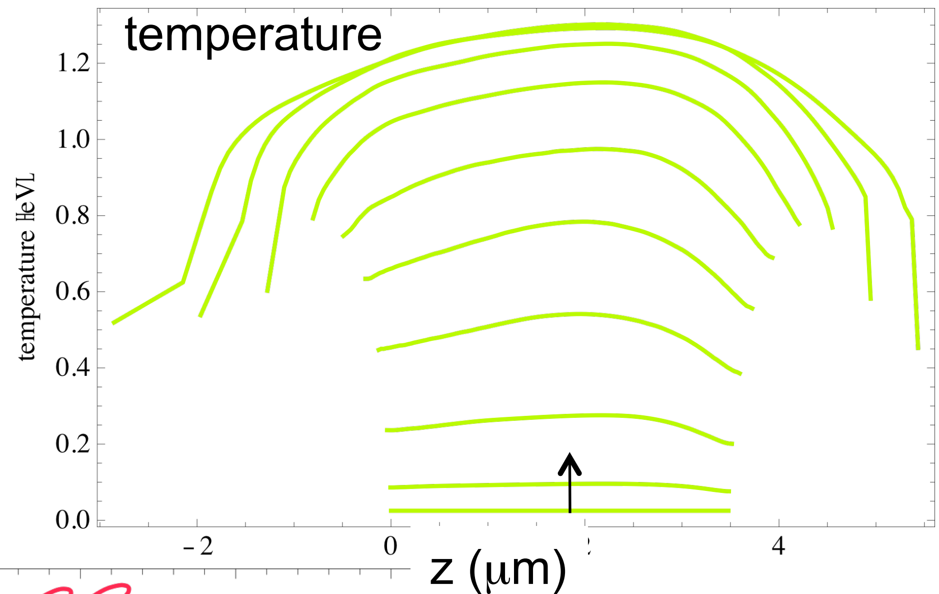
Critical point:
p=0.029 MBar
ρ=0.78 g/cm^3
T=0.945 eV

Theories and experiments place critical point between 5500 K and 12000 K (0.5 eV and 1.0 eV)

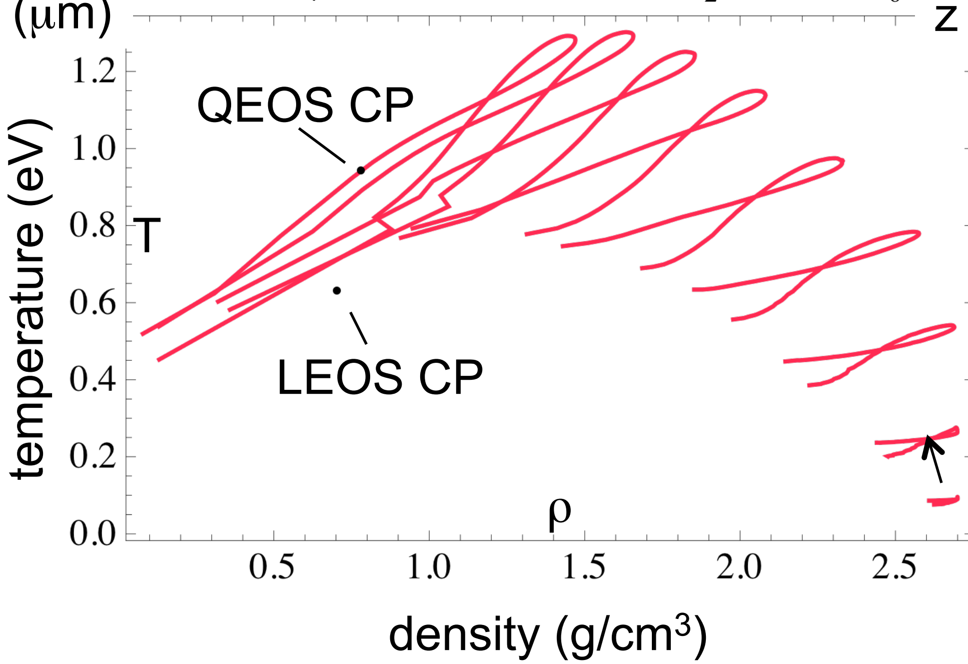
Critical point:
p=0.0065 MBar
ρ=0.70 g/cm^3
T=0.633 eV

Evolution of center of 3.5 μ thick Al foil over the heating phase (1 ns) using QEOS (using advanced NDCX II)



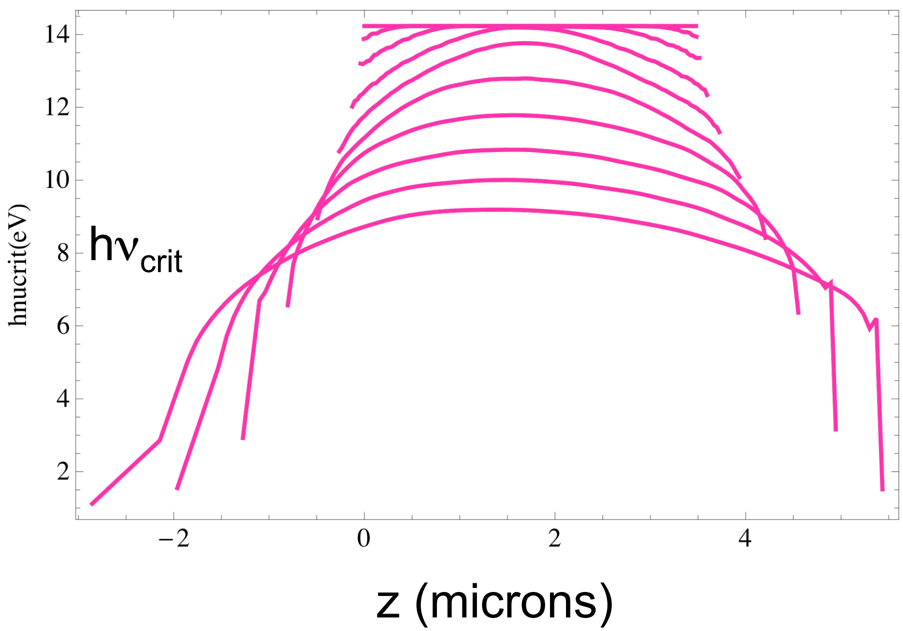


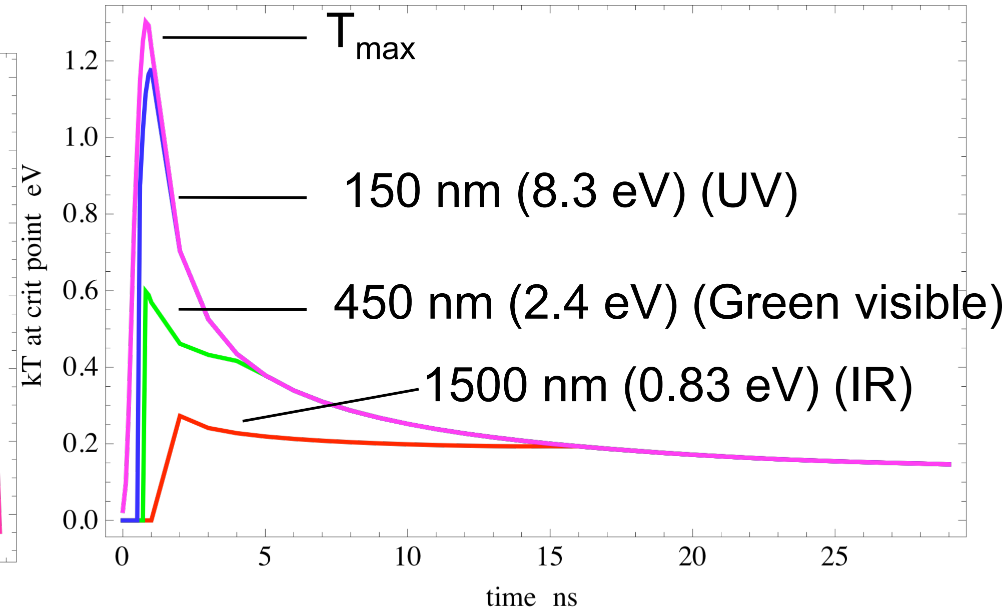
Simulations are for 20 kJ/g (30 J/cm^2) NDCX II



Snapshots separated by 0.1 ns

Evolution of the temperature T_b at the critical density for different observation frequencies





$\nu_{crit} = \omega_p/2\pi$;

Model assumes:

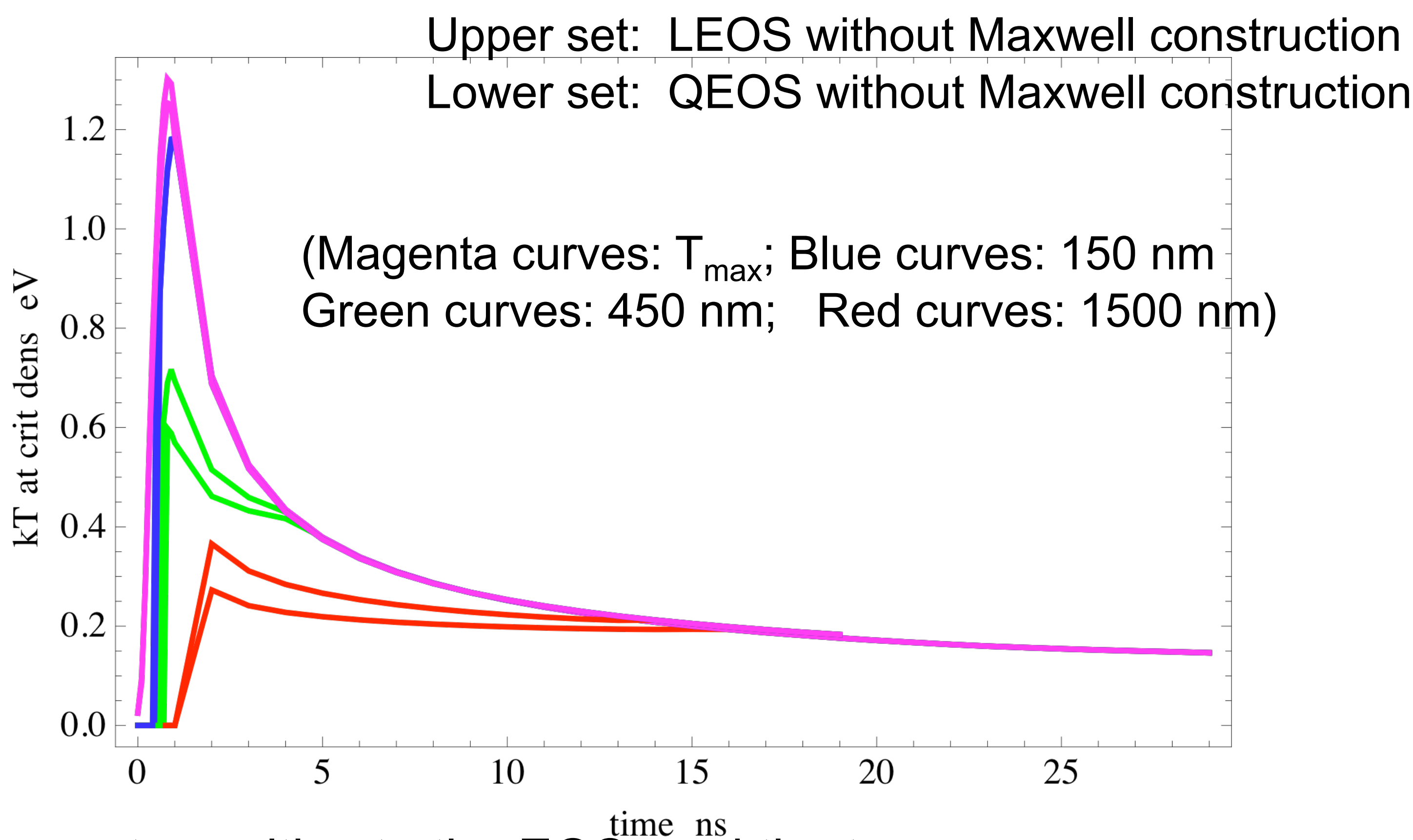
$T_b = T(h\nu_{crit})$ if $h\nu_{critmin} < h\nu < h\nu_{critmax}$

$T_b = T_{max}$ if $h\nu > h\nu_{critmax}$

$T_b = 0$ if $h\nu < h\nu_{critmin}$

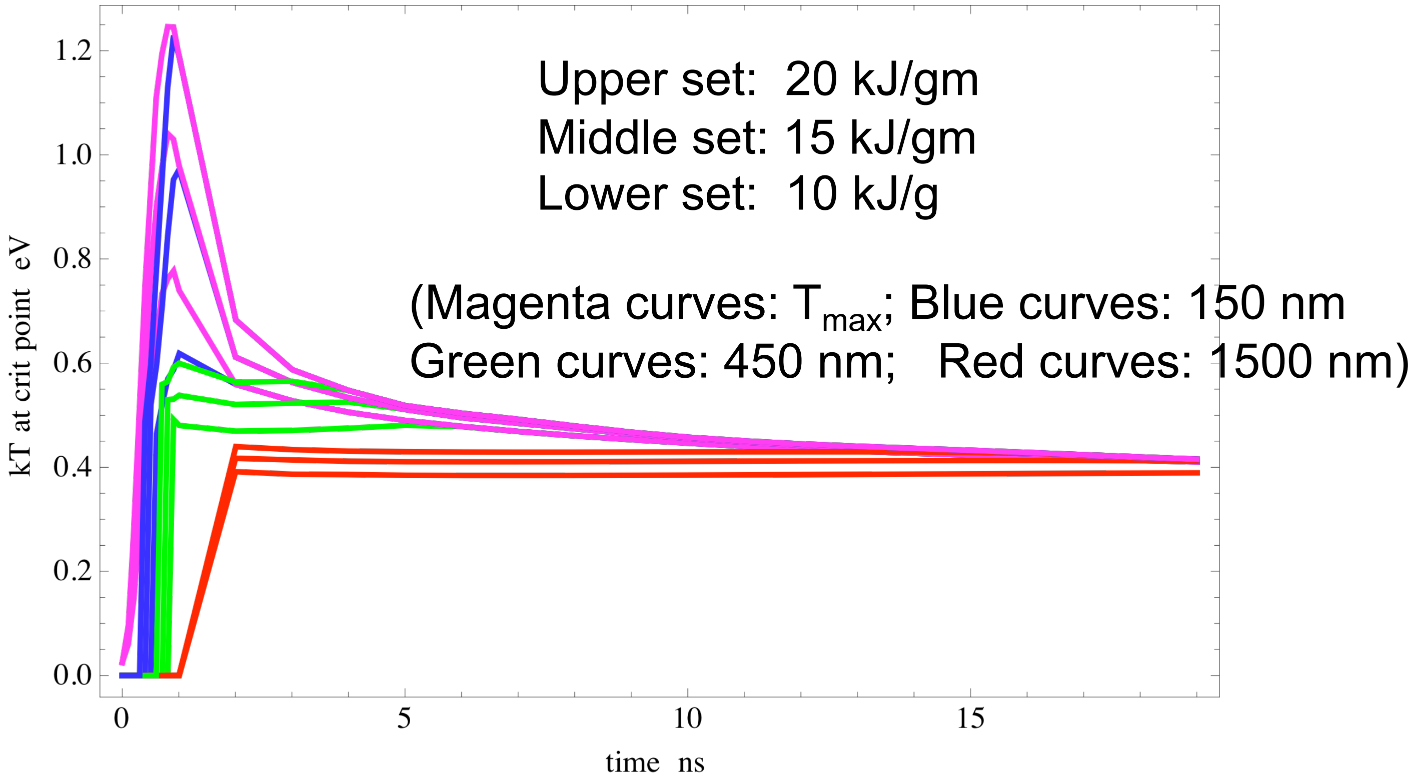
Pyrometry measurements of T_b will have significantly different profiles at different frequencies

We may compare two equations of state



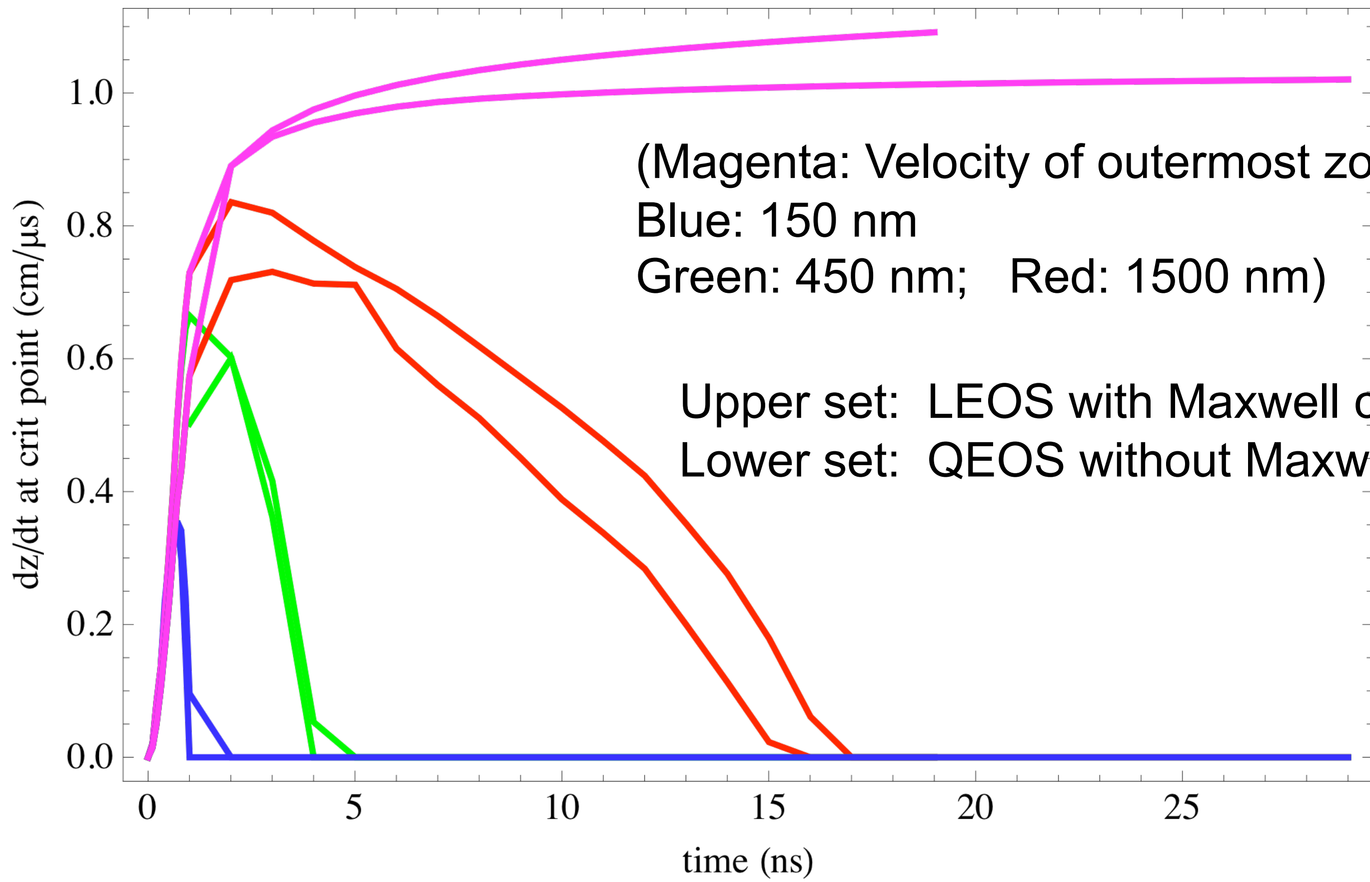
IR is most sensitive to the EOS, and the two EOS should be distinguishable

We may compare the same plots for different intensities



UV most sensitive to change in deposited energy;
IR (which samples cooler part of blowoff, less sensitive)

The velocity at the critical density as would be observed by a VISAR would also distinguish between different EOS

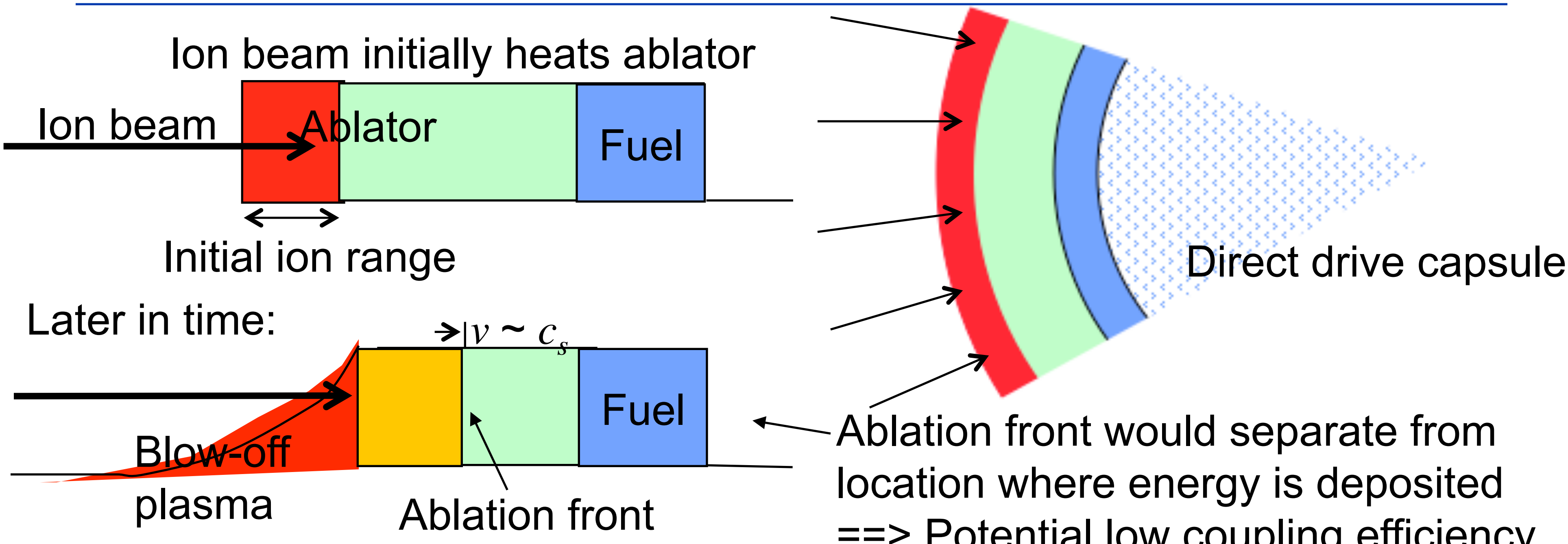


(Magenta: Velocity of outermost zone;
Blue: 150 nm
Green: 450 nm; Red: 1500 nm)

Upper set: LEOS with Maxwell construction
Lower set: QEOS without Maxwell construction

Again, the IR is best suited for distinguishing different EOS

NDCX II will also study ion beam coupling physics that is relevant to high gain direct drive targets for Inertial Fusion Energy

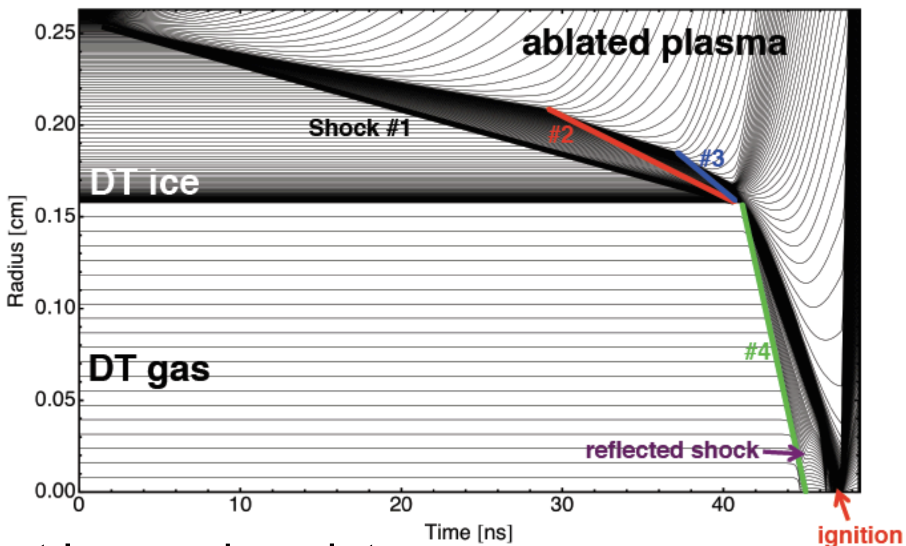


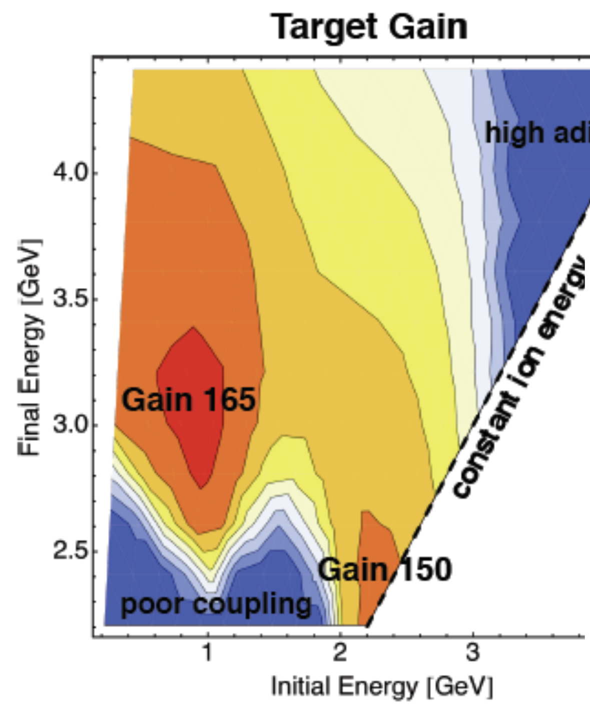
Ramping ion beam energy over the course of the pulse increases ion range:

- allows efficient coupling of beam energy into kinetic energy of fuel shell
- allows use of higher energy ions during high intensity part of pulse

Recent HYDRA simulations have quantified benefits of energy ramping in ion direct drive targets

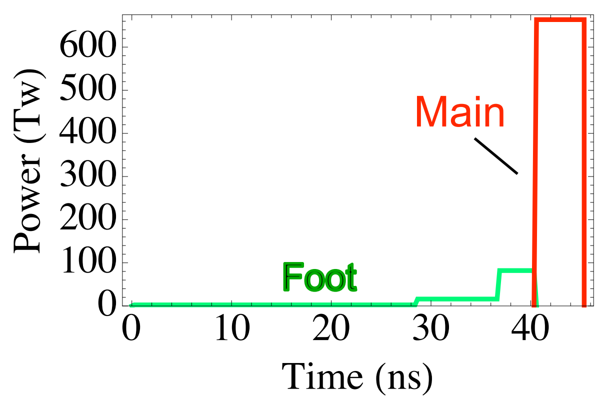
1D Simulations by M. Hay et al

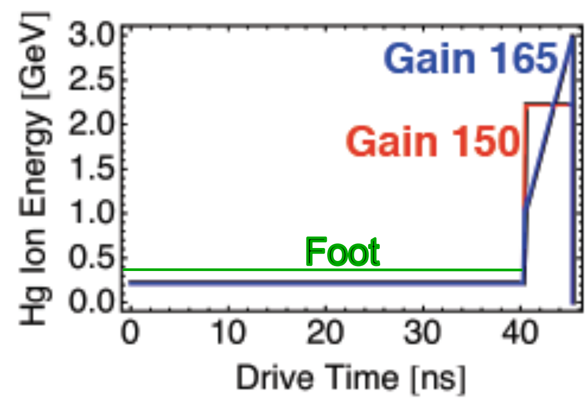




pulse energy, 3.7 MJ, power, 660 TW, & foot pulse structure held constant

rt lagrangian plot
3.7 MJ direct drive, target gain 150
3 "foot" pulses 220 MeV Hg^+
1 main pulse 2.2 GeV Hg^+





Continuous energy ramp of main pulse shows modest increase in target gain. Large benefit when ramping ion energy from "foot" pulse to "main"

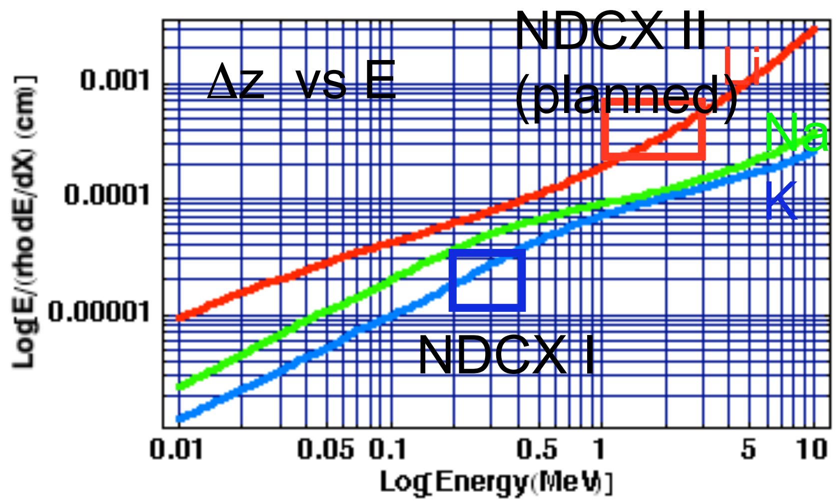
To "follow a shock," the energy ramping in NDCX II must be sufficiently fast

$$\Delta z \approx 2\mu\left(E/1\ \text{MeV}\right)$$ (solid Al)

To keep pace with the shock, (where $v_{shock} \sim c_s$) the energy slew must satisfy:

$$\frac{dE}{dt} = E\frac{c_s}{\Delta z} \cong 2.5\ \frac{\text{MeV}}{\text{ns}}$$ (solid Al)

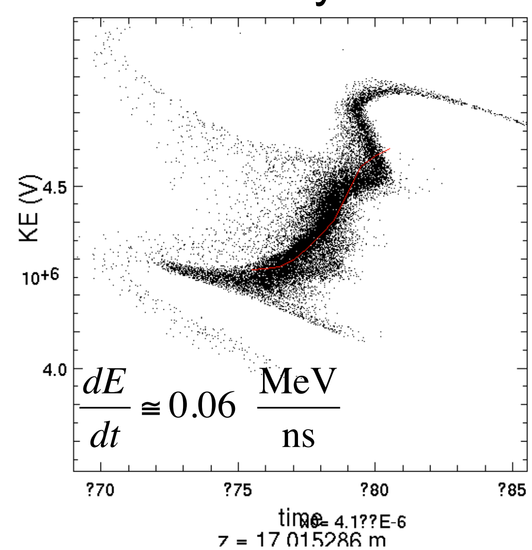
$$\frac{dE}{dt} \cong 0.10\ \frac{\text{MeV}}{\text{ns}}$$ (10% Al foam)

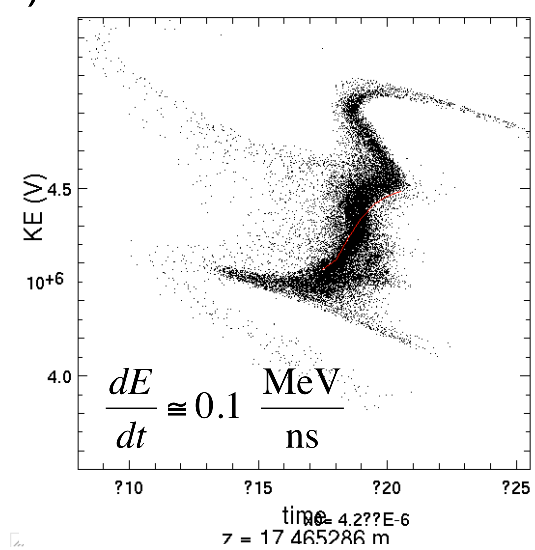


Placing foil upstream of best focus is simplest way to achieve energy ramp.

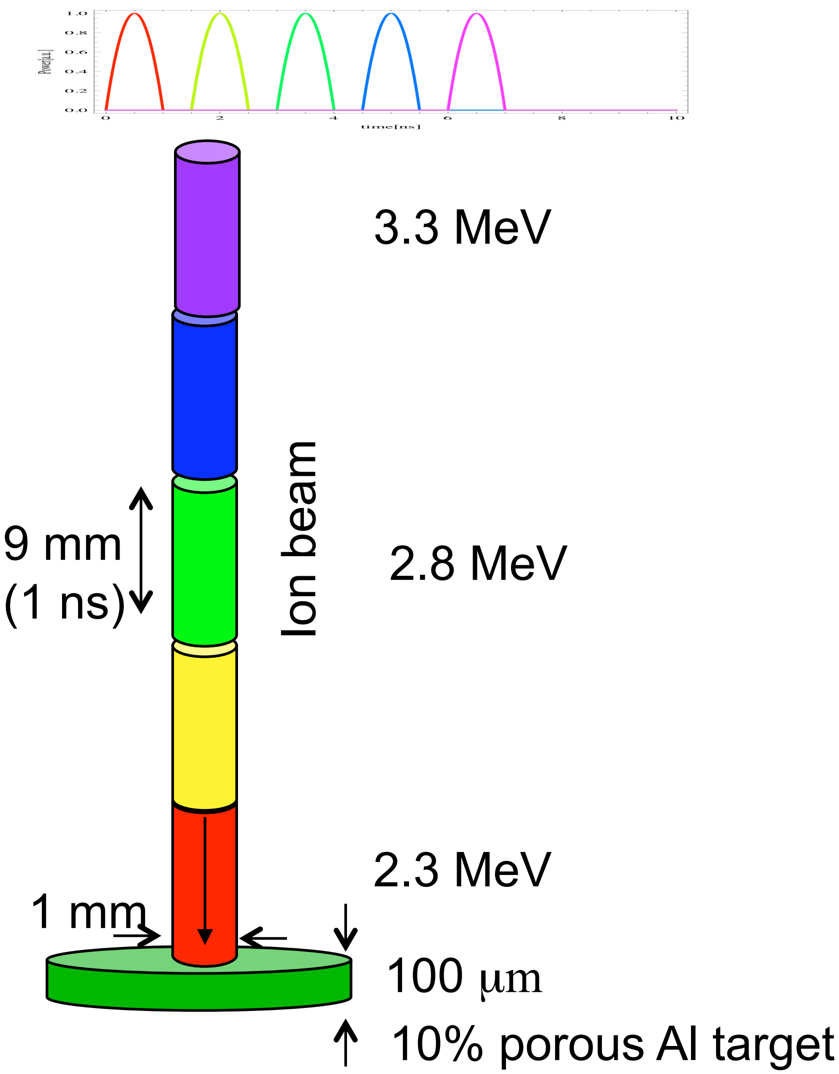
Using metallic foams or low density solids (e.g. LiH) could meet energy ramp requirement

Initial look at energy slew rate on NDCX II (WARP simulations by Dave Grote) :

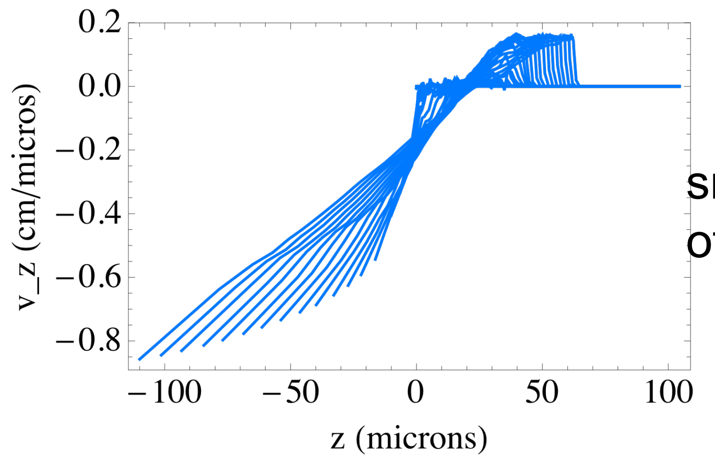




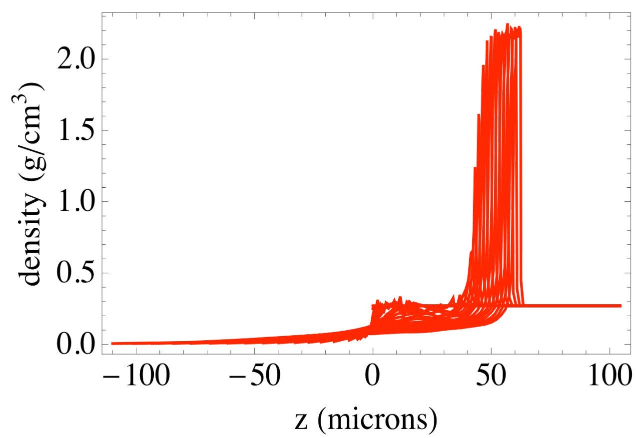
HYDRA simulations show that experiments on NDCX II can demonstrate benefits of energy ramp on coupling



6 ns "macro-pulse"

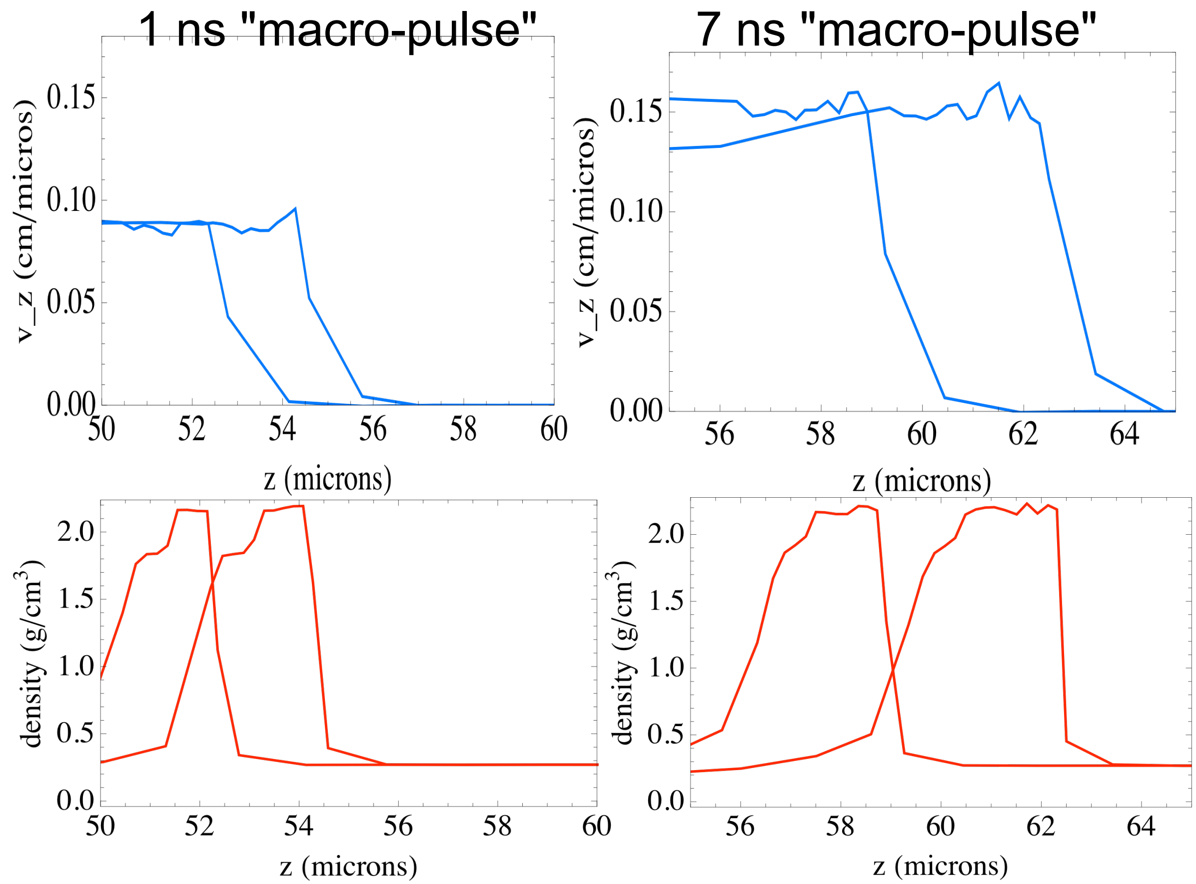


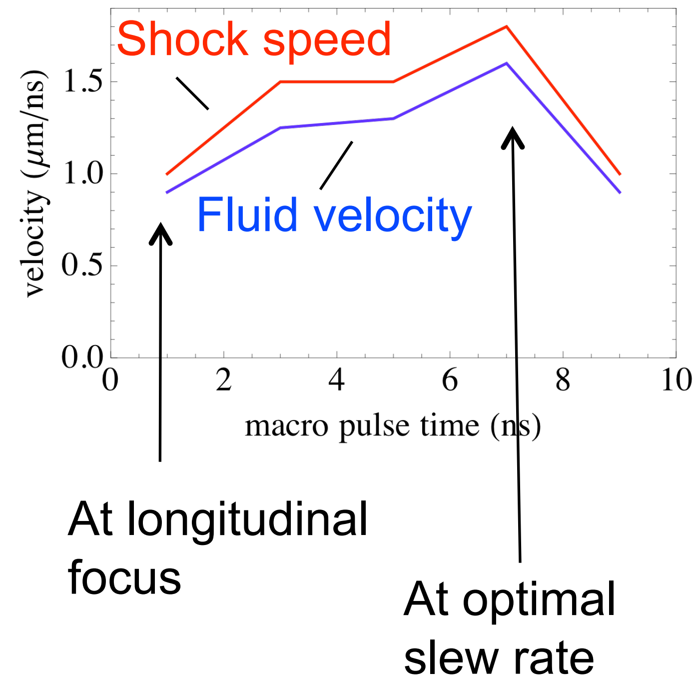
snapshots of velocity



snapshots of density

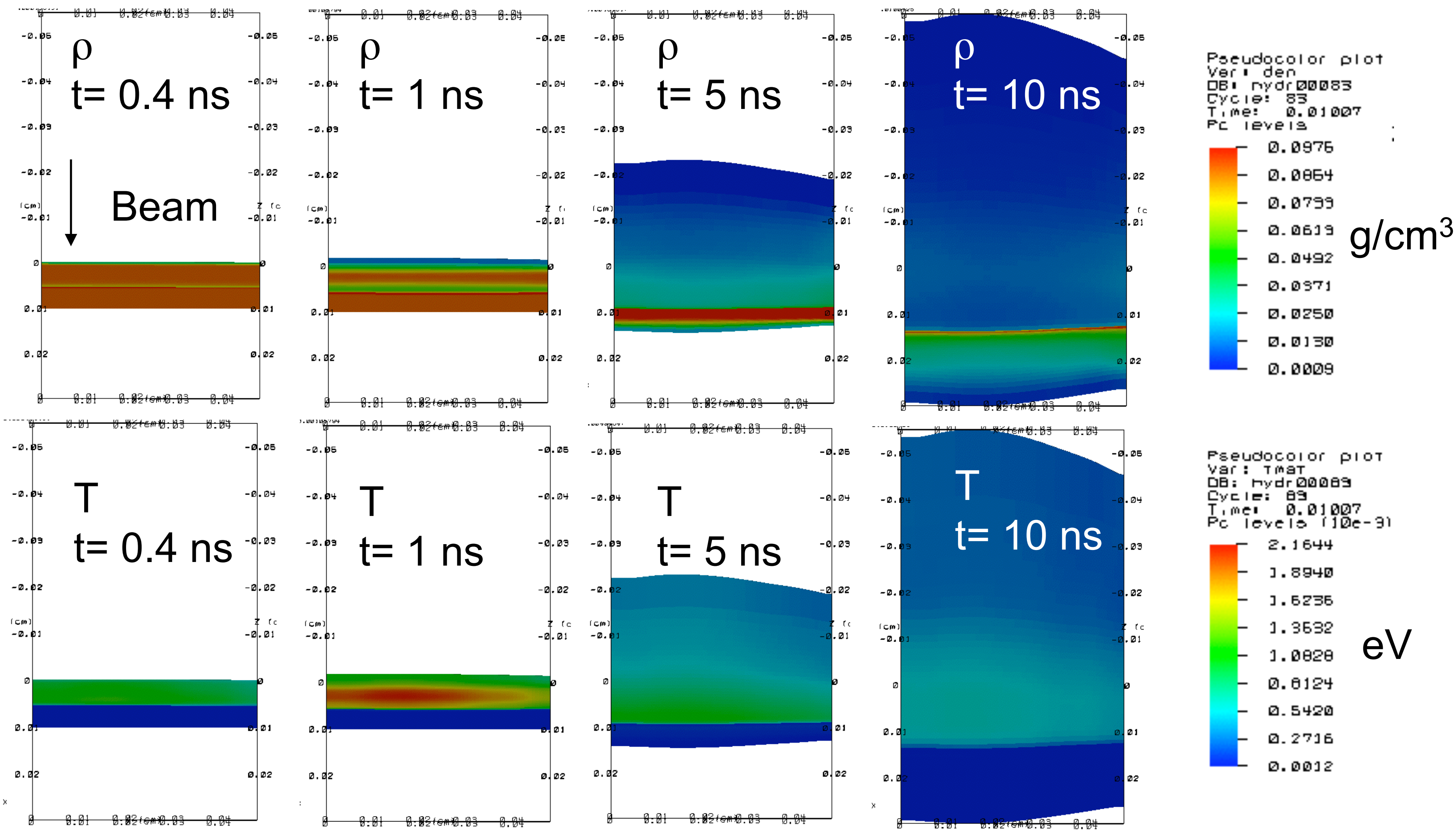
Shock positions at 18 and 20 ns illustrate the "sweet spot" at optimal slew rate





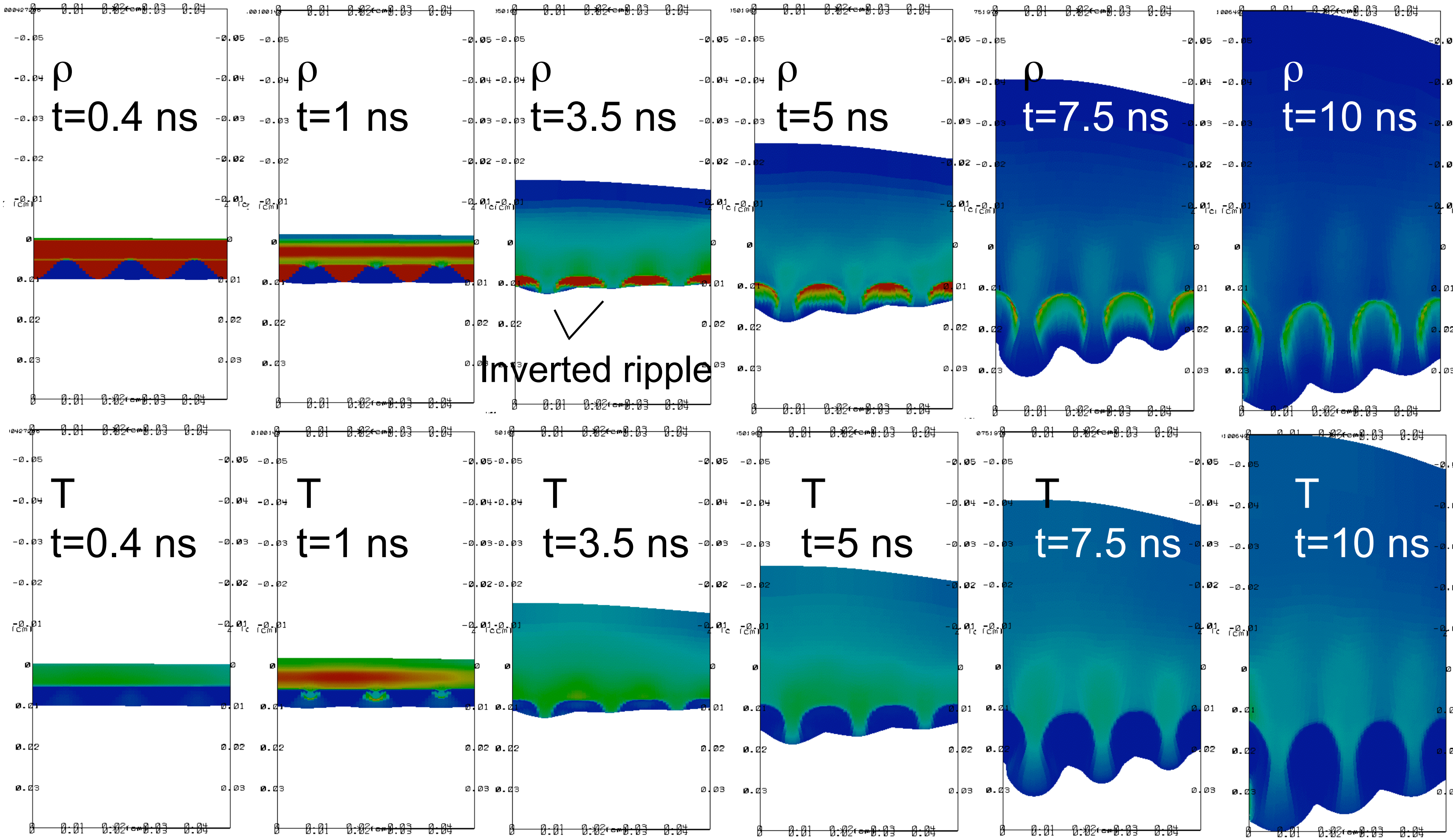
V_shock =	1.0 μ/ns	1.8 μ/ns
V_fluid =	0.9 μ/ns	1.6 μ/ns
ρ_fluid =	2.2 g/cm^3	2.2 g/cm^3

HYDRA simulations using advanced NDCX-II/IBX parameters simulate possible hydrodynamic stability experiments particular to ions

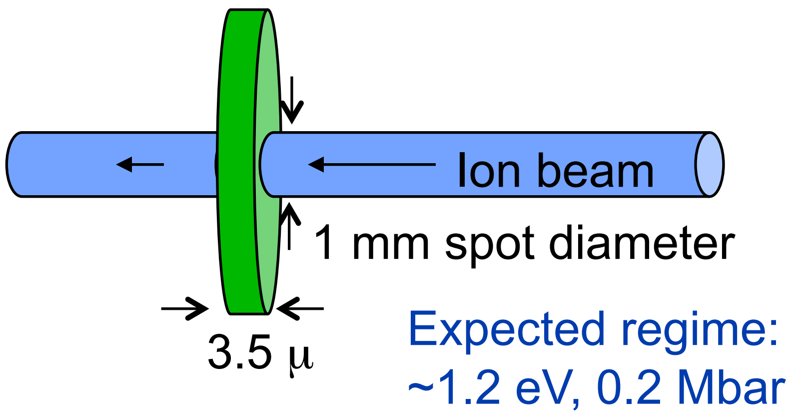


23 MeV Ne, 0.1 μC, 1 ns pulse (advanced NDCX II/IBX) impinges on 100 μ thick solid H, T=0.0012eV, ρ =0.088 g/cm3; No density ripple on surface, blowoff accelerates slab

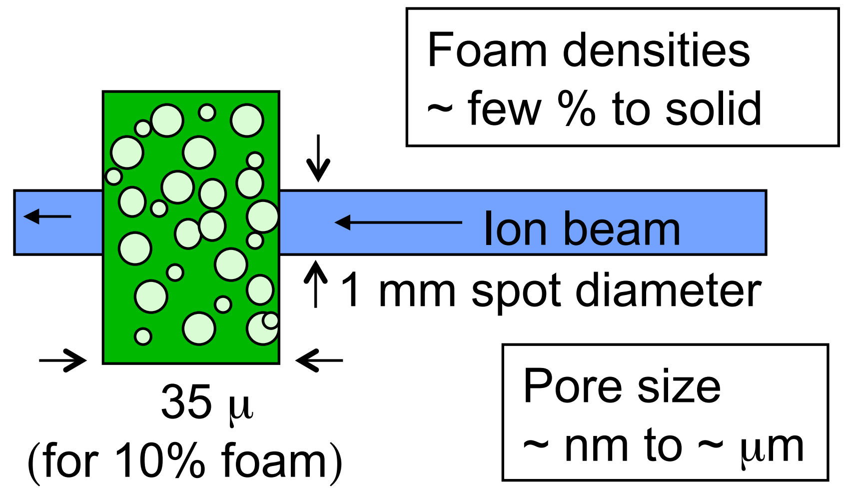
When initial surface ripple is applied, evidence for hydrodynamic instability (Richtmeyer/Meshkov) is apparent



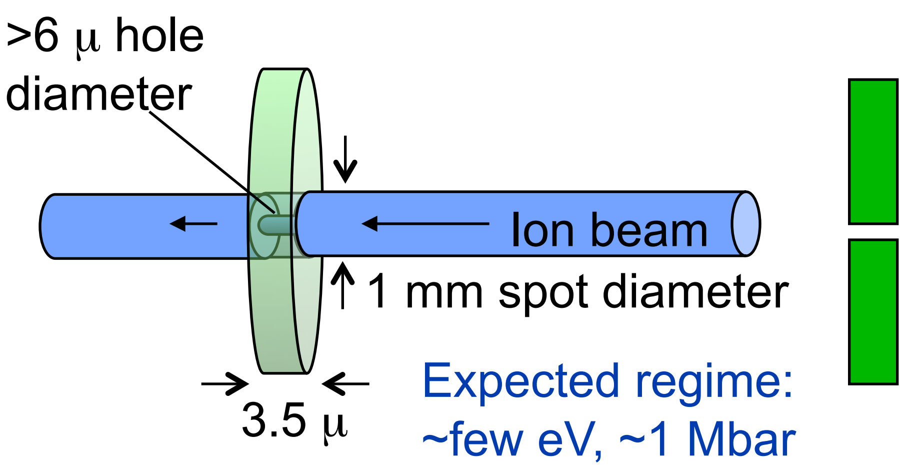
Several target options have been considered for WDM and IFE studies on NDCX II



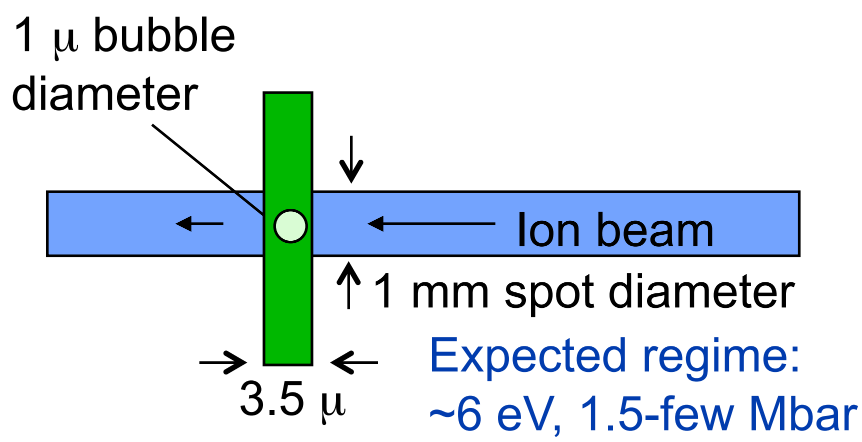
Solid planar targets



Foam planar targets



Cylindrical "bubble" targets



Spherical bubble targets

Conclusions

NDCX II will be a useful tool for both Warm Dense Matter (WDM) and Heavy Ion Fusion (HIF) applications

Recent accelerator designs achieve high pressures by reaching shorter pulse durations than initially anticipated but at lower ion energy and fluence

For WDM, NDCX II pyrometry experiments should be able to distinguish between specific equations of state (for example, QEOS and LEOS). VISAR experiments may also be able to distinguish different EOS.

For HIF, we are exploring direct drive concepts that have high coupling efficiency, by utilizing ramped ion energy with increasing range. NDCX II will be able explore a key aspect of direct drive target concept: changing ion energy to increase range over pulse. Hydrodynamic stability experiments may also be achievable for some NDCX-II parameters

Several target geometries lead to interesting material conditions
- planar targets at ~ 1 eV, .5 MBar (in Al) are predicted;
- cylindrical and spherical imploding bubbles will reach higher central temperatures and pressures, and probe ion driven hydro

Foam dynamics are of interest for both WDM and HIF applications.